AFRL-SR-AR-TR-07-0380

REPORT DOCUMENTATION PAGE

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1. REPORT DATE (DD-MM-YYYY) 1-05-2007	2. REPORT TYPE Final	3. DATES COVERED (From - To) 01-01-03 -30-06-2006
4. TITLE AND SUBTITLE Conjugate Gradient Based Reduced-Rank Signal Processing for Military Digital Communications		5a. CONTRACT NUMBER
		5b. GRANT NUMBER F49620-03-1-0149
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Michael D. Zoltowski		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Purdue University School of Electrical and Computer Engineering 465 Northwestern Ave. West Lafayette, IN 47907-2035		8. PERFORMING ORGANIZATION REPORT TR-ECE-15-2007
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Resesearch (AFOSR) Dr. Jon A. Sjogren, AFOSR/NE Program Manager Physics and Electronics	875 North Randolph St. Room 325, Suite 3112 Arlington, VA 22203 Phone: 703-696-6564	10. SPONSOR/MONITOR'S ACRONYM(S) AFOSR/NE
		11. SPONSOR/MONITOR'S
12. DISTRIBUTION / AVAILABILITY STATEMENT N/A		

13. SUPPLEMENTARY NOTES
N/A

14. ABSTRACT
The project met the objectives of developing and transitioning fundamental advances in reduced-rank adaptive signal processing. The methods have been applied to space-time equalization and interference cancellation with application to high-speed, MIMO wireless military digital communications. There was an emphasis on exploitation of second-order spatial statistics of the channel and temporal statistics of the interference to design transceivers for multi-antenna wireless communication systems. Based on space-time spreading, we showed that if signals are transmitted along the strongest eigen-direction of the channel and the weakest eigen-direction of the interference, the average SINR is maximized. We also derive optimally power loaded space-time beam-forming (STBF) schemes and show that if strong channels coincide with weak interference, then error probability reduces considerably. In order to increase transmission rates, we combined Space-Time Block Coding STBC with Space-Time Beamforming (STBF) and developed power loading schemes and low-complexity receivers. Our analytical and simulated results corroborate that STBF with optimal power loading considerably reduces error probability and channel estimator errors.

15. SUBJECT TERMS
Conjugate Gradients, Space-Time Coding, Adaptive Equalization; Intereference Cancelling

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	UNLIMITED	17	19b. TELEPHONE NUMBER (include area code) 765-494-3512

Standard Form 298 (Rev 8-98)

Conjugate Gradient Based Reduced-Rank Signal
Processing for Military Digital Communications

Air Force Office of Scientific Research

Final Technical Report
Grant/Contract Number: F49620-03-1-0149
Period Covered: 1 January 2003 - 30 June 2006

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1 SUMMARY OF FIRST YEAR EFFORT

The objectives remain the same: to identify, develop, evaluate, and demonstrate fundamental advances in reduced-rank adaptive filtering and their use in space-time equalization and interference cancellation algorithms for application to 3G+/4G MIMO wireless communication systems and Wireless LAN's. Reduced-rank processing, alternatively referred to more accurately as reduced dimension subspace processing, will be a vitally important element of future wireless communication systems, both near-term and far-term. This is due to the high dimensionality of equalizing weight vectors and/or interference cancelling weight vectors arising from a variety of factors: (i) at higher data speeds, the multipath delay spread spans a proportionately large number of data symbols thereby necessitating the use of more taps in a symbol-spaced equalizer, (ii) for MIMO communication systems, the dimensions of equalizing and/or interference cancelling weight vectors are directly scaled by the number of antennas at the transmitter and/or receiver, and (iii) judicious exploitation of polarization, an additional discriminating feature of smart antennas that can be used to differentiate amongst co-channel users, also increases weight vector dimensionality.

2 STATUS OF EFFORT

Key accomplishments during the first partial year effort were fueled by our recent discovery of an inherent relationship between the MWF and the Iterative Search Method of Conjugate-Gradients (CG). This lead to a host of new algorithmic implementations of CG-MWF that offer a number of important advantages over the original implementation of MWF. The discovery that adding a "stage" to the MWF was equivalent to taking a "step" of a CG search has lead to substantial improvements to the MWF in terms of (i) computationally efficient implementations that exploit structure in the data matrices or correlation matrices, such as Toeplitz, sparseness, etc., (ii) amenability to real-time implementation, (iii) amenability to "smart" initialization (based on information learned or statistics estimated during the process of searching for a training sequence embedded in the data, for example), (iv) easy incorporation of a-priori information, constraints, and/or "past history" for accelerated convergence, and (v) use of pre-conditioning for accelerated convergence.

Results obtained during the first partial year of this research effort have been presented at and published in the proceedings of a number of high-profile conferences on communications and signal processing sponsored by the Institute of Electrical and Electronics Engineering (IEEE) and SPIE. A list of the papers either already presented and published, or accepted for presentation and publication in 2003, is provided in Section 21.

3 ACCOMPLISHMENTS/NEW FINDINGS

A key concept underscoring this project is the difference between Signal-Independent Adaptive Beamforming and Signal-Dependent Adaptive Beamforming (ABF). The scenario assumes the formation of multiple adaptive beams, each pointed to a different "look" direction. For a linear array of N sensors, somewhere between $3N$ and $4N$ adaptive beams are formed encompassing end-fire to end-fire. In Signal-Dependent ABF, a Generalized Sidelobe Canceler (GSC) is formed for each "look" direction. Mathematically, the GSC serves to convert the constrained (quadratic) MVDR optimization problem to an unconstrained optimization problem. From an implementation point of view, the GSC essentially forces adaptation to occur in a subspace orthogonal to the steering vector for the particular "look" direction, so that the "desired" signal arriving from that direction is preserved. This serves to prevent "desired" signal cancellation, especially in cases of moderate to low sample support. Implementation of the GSC at each "look" direction requires the construction and application to the data of a blocking matrix for each "look" direction. The attendant computational complexity is substantial. Methods for reducing this complexity are the focus of this proposed effort.

1

Further key to this effort is reduced-rank ABF to deal with issues related to inadequate sample support. Two forms of reduced rank adaptive processing are considered in this proposal: Principal Components Inverse (PCI) and Conjugate Gradients-Multistage Wiener Filtering (CG-MWF). A Signal-Independent PCI algorithm based on eigenvectors of the sample correlation matrix does not effect a GSC for each "look" direction. As a result, SI-PCI has the computational benefit of using the same eigenvalues and eigenvectors to determine the respective ABF for each "look" direction. However, this computational expediency comes at a cost relative to performance, as evidenced in the simulation results presented in Figure 1.

The simulations presented in Figure 1 involved 14 azimuthal channels with 16 time-delay taps per channel for 224 total degrees of freedom. In addition to the desired source, there were four interfering sources at $-60°$, $-30°$, $45°$, and $60°$ with respective SNR's of 40 dB, 20 dB, 40 dB, and 40 dB. The results presented were obtained with 224 data samples; this represents a relatively low sample support case where the number of snapshots is equal to the dimension of the wideband ABF vector.

Signal-Dependent CG-MWF yields its best performance at a "rank" of 64, where it is about 2 dB below the best SINR that could be achieved with infinite sample support. SD-PCI achieves the same best SINR as Signal-Dependent CG-MWF, but at a rank of approximately 90. Signal-Independent PCI (DMR) reaches its best performance at a rank of around 175 and is about 6 dB below the optimal SINR. Clearly, SI-PCI yields inferior performance relative to Signal-Dependent PCI and CG-MWF.

On the other hand, though, Signal-Dependent PCI requires a "new" dominant eigenvector computation for each "new" look direction. That is, for each "look" direction, SD-PCI requires the computation of the dominant eigenvectors of a matrix obtained by pre- and post-multiplying the sample correlation matrix by a blocking matrix corresponding to that "look" direction. The computational complexity of Signal-Dependent PCI has heretofore prevented its use in practice, despite its substantial performance improvement over SI-PCI (DMR).

As part of the continuing effort, therefore, we plan to investigate and develop efficient Signal-Dependent forms of both CG-MWF and PCI. We will initially focus on computationally efficient forms of Signal-Dependent CG-MWF. This is because the Conjugate-Gradient algorithmic basis for CG-MWF lends itself well to a number of novel methods for reducing the complexity of effecting the GSC and attendant blocking matrix for each "look" direction. However, insight gained from the development of computationally efficient algorithms for Signal-Dependent CG-MWF will lead to computationally efficient means of implementing a Signal-Dependent form of DMR (SD-PCI).
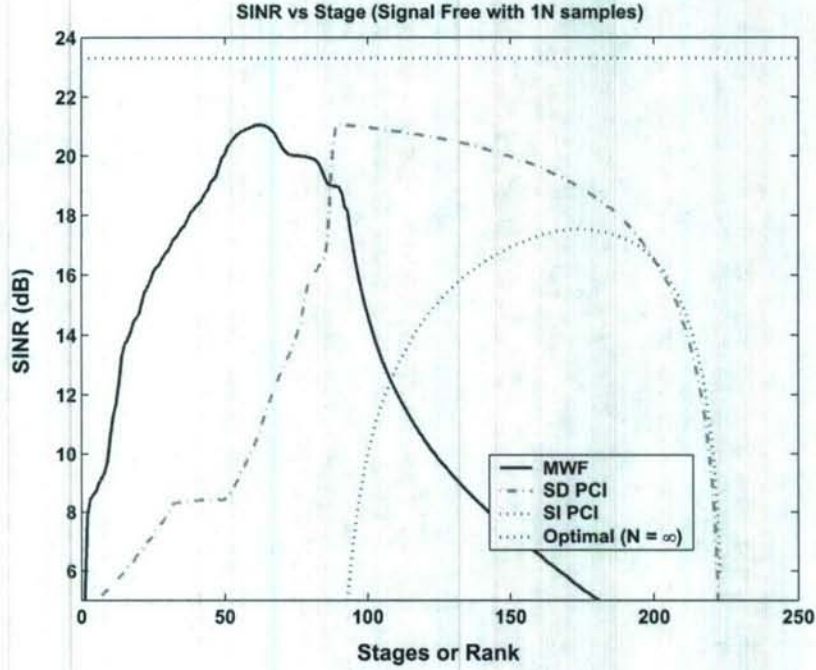
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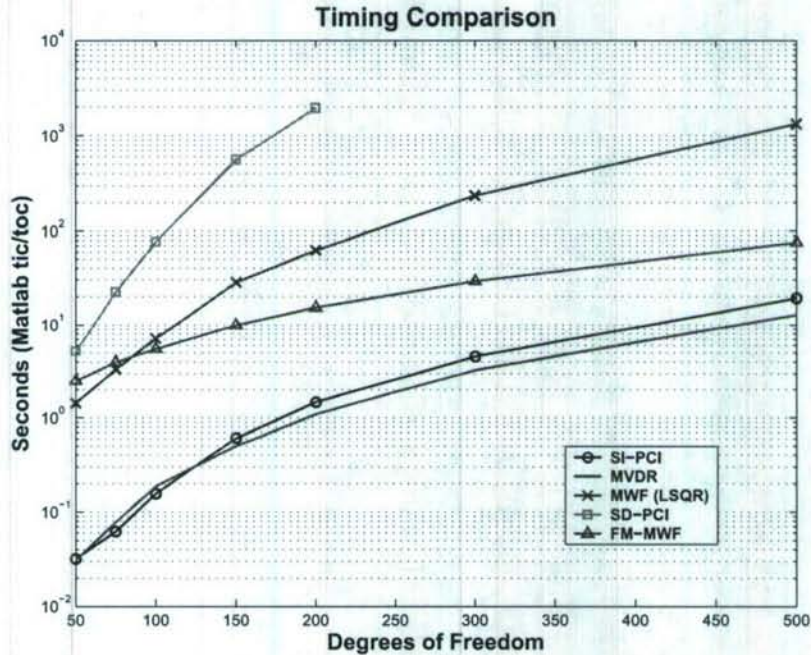

Figure 2. Fast Multibeam CG-MWF based on diagonalized sample correlation matrix offers substantially lower complexity than SD-PCI, and lower complexity than "standard" CG-MWF. Fast Multibeam CG-MWF offers complexity comparable to SI-PCI for large sensor arrays.

4 PERSONNEL SUPPORTED

Faculty: Michael D. Zoltowski (PI)

Graduate Research Assistant: Peilu Ding

5 PUBLICATIONS

5.1 Journal Papers Published and/or Accepted

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2. S. Ozen and M. D. Zoltowski, "Time-of-Arrival (TOA) Estimation Based Structured Sparse Channel Estimation Algorithm, with Applications to Digital TV Receivers," *Proc. of 2003 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Hong Kong, 6-10 April 2003, Vol. IV, pp. 413-416.

3. B. Breinholt, M. D. Zoltowski, T. A. Thomas, and K. Baum, "Space-Time Equalization and Interference Cancellation with Convolutional Coding for MIMO OFDM," *Proc. of 2003 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Hong Kong, 6-10 April 2003, Vol. IV, pp. 481-484.

4. A. Tarr and M. D. Zoltowski, "R-Conjugate Codes for Multi-Code CDMA," accepted for presentation at and publication in (Paper no. 2440 - Lecture) *Proc. of 2003 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Hong Kong, 6-10 April 2003, Vol. IV, pp. 145-148.

5. G. Dietl and M. D. Zoltowski, "Multi-Stage MMSE Decision Feedback Equalization for EDGE," *Proc. of 2003 IEEE Int'l Conf. on Acoustics, Speech, and Signal Processing*, Hong Kong, 6-10 April 2003, Vol. IV, pp. 413-416.

6. A. Tarr and M. D. Zoltowski, "Design of codes for multicode CDMA based on correlation feedback from, receiver," *SPIE's International Symposium on AeroSense*, Orlando, Florida, **SPIE Proc. Vol. 5100: Digital Wireless Communications V**, 21-22 April 2003. pp. 261-266.

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7. M. D. Zoltowski, W. J. Hillery, and M. Fimoff, "Feedback tap value constrained decision feedback equalizers for reduced error propagation," *SPIE's International Symposium on AeroSense,* Orlando, Florida, **SPIE Proc. Vol. 5100: Digital Wireless Communications V**, 21-22 April 2003, pp. 192-203.

8. S. Ozen and M. D. Zoltowski, "Structured Channel Estimation Algorithm based on estimating Time-of-Arrivals (TOAs), with Applications to Digital TV Receivers," *SPIE's International Symposium on AeroSense,* Orlando, Florida, **SPIE Proc. Vol. 5100: Digital Wireless Communications V**, 21-22 April 2003, pp. 169-180.

9. John Hiemstra, Michael Zoltowski, and J. Scott Goldstein, "Recursive and Knowledge-Aided Implementations of the Multistage Wiener Filter," *2003 IEEE Radar Conference (RadarCon03),* Huntsville AL, 5-8 May 2003.

6 INTERACTIONS/TRANSITIONS:

6.1 A. Participation/presentations at meetings, conferences, seminars, etc

- see conference papers listed in Section 5.2

- Conference Co-Chair, Symposium on Digital Wireless Communications V, AEROSENSE: Aerospace/Defense Sensing, Simulation and Controls, Orlando, FL, 21-22 April 2003.

- Area Editor, IEEE Signal Processing Magazine, in charge of all feature articles, appointed May 2002 for three year term.

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- Vice-Chairman, Sensor Array and Multichannel (SAM) Technical Committee, First Term: 1 January 2001 - 31 December 2003.

6.2 C. Transitions

An all-day tutorial entitled "TUTORIAL ON REDUCED-RANK ADAPTIVE FILTERING BASED ON THE MULTI-STAGE WIENER FILTER" was presented on 18 June 2002 to the CITE Group at Rome Labs headed by Dr. Bruce Suter. Dr. Bruce Suter and CITE will implement and assess the performance of the Conjugate-Gradient based reduced rank filtering schemes developed as part of this project. We will continue to report of this ongoing transition as it progresses.

7 NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None.

8 HONORS/AWARDS

1. **2002 Technical Achievement Award of IEEE Signal Processing Society.** *Web site:* http://www.ieee.org/organizations/society/sp/techachv.html , "The Technical Achievement Award

honors a person who, over a period of years, has made outstanding technical contributions to the theory and/or practice in technical areas within the scope of the Society, as demonstrated by publications, patents, or recognized impact on the field. The prize shall be $1500, a plaque and a certificate, and shall be presented at the ICASSP meeting held during the Spring following selection of the winner." The award was to be conferred at ICASSP 2003 in Hong Kong during 6-10 April 2003 (canceled due to SARS, but award mailed.)

2. **2003 Distinguished Lecturer for IEEE Signal Processing Society.** *Web site:* http://www.ieee.org/organizations/society/sp/dlinfo.html There are six Distinguished Lecturers chosen each year to represent the Society by giving lectures on their research around the world. The web site for the SPS Distinguished Lecturer Program indicates that "The Society's Distinguished Lecturer Program provides means for chapters to have access to individuals who are well known educators and authors in the fields of signal processing, to lecture at Chapter meetings."

3. **Advisory Council for the Department of Electical and Computer Engineering at Drexel University.** August 2002-present. First meeting attended on 3 December 2003. Also, highlight article in Drexel University's (1) 2003 College of Engineering Brochure, (2) Spring 2003 Electrical and Computer Engineering (ECE) Newsletter, and (3) ECE Web Page's Alumni News Section.

9 SUMMARY OF SECOND YEAR EFFORT

The objectives remain the same: to identify, develop, evaluate, and demonstrate fundamental advances in reduced-rank adaptive filtering and their use in space-time equalization and interference cancellation algorithms for application to 3G+/4G MIMO wireless communication systems and Wireless LAN's. Reduced-rank processing, alternatively referred to more accurately as reduced dimension subspace processing, will be a vitally important element of future wireless communication systems, both near-term and far-term. This is due to the high dimensionality of equalizing weight vectors and/or interference cancelling weight vectors arising from a variety of factors: (i) at higher data speeds, the multipath delay spread spans a proportionately large number of data symbols thereby necessitating the use of more taps in a symbol-spaced equalizer, (ii) for MIMO communication systems, the dimensions of equalizing and/or interference cancelling weight vectors are directly scaled by the number of antennas at the transmitter and/or receiver, and (iii) judicious exploitation of polarization, an additional discriminating feature of smart antennas that can be used to differentiate amongst co-channel users, also increases weight vector dimensionality.

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Key accomplishments during the first partial year effort were fueled by our recent discovery of an inherent relationship between the MWF and the Iterative Search Method of Conjugate-Gradients (CG). This lead to a host of new algorithmic implementations of CG-MWF that offer a number of important advantages over the original implementation of MWF. The discovery that adding a "stage" to the MWF was equivalent to taking a "step" of a CG search has lead to substantial improvements to the MWF in terms of (i) computationally efficient implementations that exploit structure in the data matrices or correlation matrices, such as Toeplitz, sparseness, etc., (ii) amenability to real-time implementation, (iii) amenability to "smart" initialization (based on information learned or statistics estimated during the process of searching for a training sequence embedded in the data, for example), (iv) easy incorporation of a-priori information, constraints, and/or "past history" for accelerated convergence, and (v) use of pre-conditioning for accelerated convergence.

Results obtained during the first partial year of this research effort have been presented at and published in the proceedings of a number of high-profile conferences on communications and signal processing sponsored by the Institute of Electrical and Electronics Engineering (IEEE) and SPIE. A list of the papers either already presented and published, or accepted for presentation and publication in 2003, is provided in Section 21.

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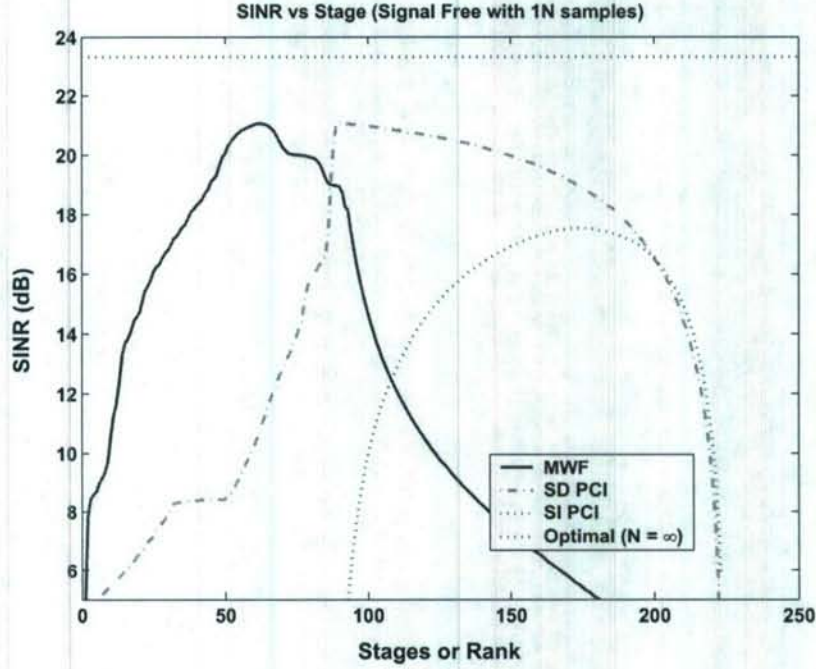
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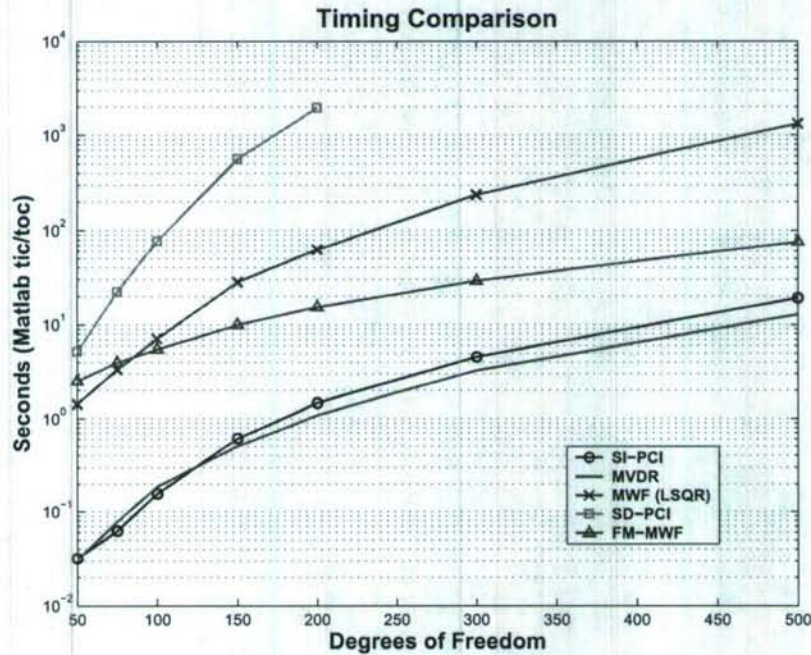

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Graduate Research Assistant: Peilu Ding

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1. **2002 Technical Achievement Award of IEEE Signal Processing Society.** *Web site:* http://www.ieee.org/organizations/society/sp/techachv.html , "The Technical Achievement Award

honors a person who, over a period of years, has made outstanding technical contributions to the theory and/or practice in technical areas within the scope of the Society, as demonstrated by publications, patents, or recognized impact on the field. The prize shall be $1500, a plaque and a certificate, and shall be presented at the ICASSP meeting held during the Spring following selection of the winner." The award was to be conferred at ICASSP 2003 in Hong Kong during 6-10 April 2003 (canceled due to SARS, but award mailed.)

2. **2003 Distinguished Lecturer for IEEE Signal Processing Society.** *Web site:* http://www.ieee.org/organizations/society/sp/dlinfo.html There are six Distinguished Lecturers chosen each year to represent the Society by giving lectures on their research around the world. The web site for the SPS Distinguished Lecturer Program indicates that "The Society's Distinguished Lecturer Program provides means for chapters to have access to individuals who are well known educators and authors in the fields of signal processing, to lecture at Chapter meetings."

3. **Advisory Council for the Department of Electical and Computer Engineering at Drexel University.** August 2002-present. First meeting attended on 3 December 2003. Also, highlight article in Drexel University's (1) 2003 College of Engineering Brochure, (2) Spring 2003 Electrical and Computer Engineering (ECE) Newsletter, and (3) ECE Web Page's Alumni News Section.

17 SUMMARY OF THIRD YEAR EFFORT

The objectives still include identification, development, evaluatation, and demonstration of fundamental advances in reduced-rank adaptive filtering and their use in space-time equalization and interference cancellation algorithms for application to 3G+/4G MIMO wireless communication systems and Wireless LAN's. In addition, the objectives have advanced to include broader improvements in MIMO wireless communications. Reduced-rank processing is a vitally important element of future wireless communication systems due to the high dimensionality of equalizing weight vectors and/or interference cancelling weight vectors arising from a variety of factors: (i) higher data speeds, (ii) multi-antenna communication systems, and (iii) polarimetric processing.

18 STATUS OF EFFORT

Full-diversity, full-rate (FDFR) space-time codes for open loop multiple antenna systems achieve both high data rate and good performance but come with very high decoding complexity. Key accomplishments during this phase of the research include a low complexity adaptive FDFR design for closed loop multiple-input, multiple-output (MIMO) systems. With only partial channel subspace knowledge at the transmitter, we adapt the open loop FDFR code to the channel to maintain the special layer structure of the code at the receiver. That special layer structure enables us to decouple the joint detection over dimension $\mathbf{C^{N_t^2}}$ into N_t individual decoders of dimension $\mathbf{C^{N_t}}$ where N_t is the number of transmit antennas. This can also be seen as combining the channel diagonalization with signal diversity rotation. The performance of this scheme has been analyzed. It was shown that the full diversity property is maintained in the adaptive design. Adaptive power loading was incorporated to further exploit Channel State Information (CSI) in term of the knowledge of the singular values of the channel. The optimal loading schemes are derived for systems with linear receivers.

Results obtained during the phase of the research effort have been presented at and published in the proceedings of a number of high-profile conferences on communications and signal processing sponsored by the Institute of Electrical and Electronics Engineering (IEEE) and SPIE. A list of the papers either already presented and published, or accepted for presentation and publication in 2005, is provided in Section 21.

19 ACCOMPLISHMENTS/NEW FINDINGS

It is well established that multiple antenna transceivers are a key enabling technology that makes reliable high data rate communication possible through wireless channels. The multiple antennas installed at both the transmitter and the receiver create a multiple-input and multiple-output (MIMO) link which offers spatial diversity as well as multiplexing gain. The diversity gain can reduce the error rate while multiplexing gain improves the date rate. Over the past several years, a number of transmit schemes have been proposed to obtain the advantages provided by multiple antennas at the transmitter.

Among those transmit diversity schemes proposed for open loop[1] MIMO systems, full-diversity, full-rate (FDFR) space-time coding is attractive because it achieves both high data rate and full diversity gain. For a quasi-static Rayleigh fading channel with N_t transmit antennas and N_r receive antennas, the FDFR code transmits $\min(N_t, N_r)$ symbols per channel use with diversity gain $N_t N_r$. However, the rate increase and diversity gain come at the price of high decoding complexity at the receiver. For example, when $N_t = N_r = 4$ and a QPSK constellation is used, the maximum likelihood (ML) decoding of one FDFR codeword requires a search over $4^{16} \approx 4 \times 10^9$ lattice points!

On the other hand, when the transmitter knows full or partial channel state information (CSI), we have a closed loop MIMO system. The CSI available at the MIMO transmitter has been shown to be highly advantageous for further optimizing the transmission scheme to achieve higher link capacity

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[1]Open loop transmitters are assumed to have no knowledge about instantaneous channel conditions.

and throughput, improve the signal noise ratio (SNR) at the receiver, and provide simple means to exploit transmit diversity. Many practical systems now take advantage of having some amount of CSI at the transmitter. Usually, closed loop MIMO systems can be accomplished by employing CSI feedback for frequency division duplexing (FDD) or using reciprocity of the channel in time division duplexing (TDD) systems.

In this phase of the research effort, we considered FDFR space-time coding when partial or full CSI is available at the transmitter. We utilized the transmitter CSI to effectively reduce the decoding complexity at the receiver and even improve the performance. A low complexity adaptive design was developed for FDFR space-time codes. Because i) the FDFR code matrix has a layer structure such that every layer only depends on one symbol subblock of length N_t and ii) every layer is separated in the code matrix, we diagonalize the MIMO channel based on the singular value decomposition. This only requires channel subspace knowledge at the transmitter and involves only linear processing at the transmitter and receiver. Thus, the special layer structure in the FDFR codeword is still maintained after transmission through the channel. This layer structure enables the joint detection over dimension $\mathbf{C}^{N_t^2}$ to be decoupled into N_t individual decoders of dimension $\mathbf{C}^{N_t}$. This effectively reduces the decoding complexity for both the ML receiver, sphere decoder, and even the linearly receiver. The resulting scheme can be seen as combined channel diagonalizing and signal diversity rotation, which was first developed for single-input single-output Rayleigh fading channels. In the scheme that we have developed, the equivalent fading coefficients are the singular values of the MIMO channel matrix. Our performance analysis shows that the proposed low complexity adaptive FDFR code still has the full diversity property.

When full channel knowledge (mainly the knowledge of the singular values of the channel) is available at the transmitter, further exploitation of CSI is possible through adaptive power loading. Since it is intractable to derive the closed form optimal power loading coefficients under an ML criterion, we focussed on power loading for systems with linear minimum mean square error (MMSE) receivers. Several different criteria are considered for deriving optimal loading solutions. The solutions are similar to the power loading schemes in optimal linear transceiver designs. The resulting scheme can be alternatively implemented as spatial multiplexing with adaptive linear precoding. While most of the adaptive spatial multiplexing schemes for closed loop MIMO are optimized under linear receivers, the main feature of the scheme that we have developed is the use of signal diversity rotation matrix in precoding which promises full diversity gain when ML or sphere decoding are used.

Our simulations reveal that the adaptive FDFR design without power loading achieves the full diversity order with an additional SNR gain over open loop FDFR codes but only has the decoding complexity of VBLAST with sphere decoding. Note that power loading can further improve the performance without the increase of complexity by exploiting more channel knowledge.

Thus, a low complexity adaptive FDFR code for closed loop MIMO systems has been developed. Knowlegde of the input singular vector information of the channel at the transmitter is used to diagonalize the channel with linear processing so that the decoding complexity at the receiver is greatly reduced through decomposing the joint detection into separate decoding of subblocks (or layers) while the diversity gain is maintained. The performance was further improved by incorporating power loading adaptive to the singular values of the channel. Several power loading schemes for different criteria were examined and we derived closed form optimal loading solutions under linear MMSE receiver for each given criteria. The transmission scheme was alsoimplemented as spatial multiplexing with precoding,yielding a full diversity adaptive spatial multiplexing scheme.

In the future, we will investigate the extension of the results to codes achieving the optimal diversity-vs-multiplexing tradeoff of MIMO channels. We also plan to conduct further research towards obtaining a tighter lower bound of the error probability, especially for the correlated channel situation.

20 PERSONNEL SUPPORTED

Faculty: Michael D. Zoltowski (PI)

Graduate Research Assistant: Peilu Ding

21 PUBLICATIONS

21.1 Journal Papers Published and/or Accepted

1. Tai-Ann Chen, M. P. Fitz, S. Li, and M. D. Zoltowski, "Two Dimensional Space-Time Pilot Symbol Assisted Demodulation for Frequency Nonselective Rayleigh Fading Channels," *IEEE Transactions on Communications*, vol. 52, no. 6, June 2004, pp. 953-963.

2. Wong, K.T.; Linshan Li; Zoltowski, M.D.; "Root-MUSIC-based direction-finding and polarization estimation using diversely polarized possibly collocated antennas," *Antennas and Wireless Propagation Letters*, Volume: 3 , Issue: 8 , 2004, Pages: 129 - 132.

3. M. B. Breinholt, **H. Jung**, and M. D. Zoltowski, "Space-Time Alignment for Asynchronous Interference Suppression in MIMO OFDM Cellular Communications," **Special Issue on MIMO Communications**, *Wiley's Journal of Wireless Communications and Mobile Computing*, pp. 755-771, vol. 4, 2004.

21.2 Conference Papers Published and/or Accepted

1. Hillery, W.J.; Zoltowski, M.D.; Fimoff, M.; "Computation of a constrained decision feedback equalizer for reduced error propagation," *Wireless Communications and Networking Conference, 2004. WCNC. 2004 IEEE*, Volume: 4 , 21-25 March 2004, Pages: 2438 - 2443.

   item Weippert, M.E.; Hiemstra, J.D.; Goldstein, J.S.; Sabio, V.J.; Zoltowski, M.D.; Reed, I.S.; "Efficient adaptive reduced-rank multibeam processing," *Proceedings of 2004 IEEE Aerospace Conference,* ,Volume: 3 , 6-13 March 2004, Pages: 1935-1941.

2. M. D. Zoltowski and E. Santos, "Advances in Reduced-Rank Adaptive Beamforming," *SPIE 2004 Defense and Security Symposium*, Orlando, Florida, **SPIE Proc. Digital Wireless Communications VI**, 12-16 April 2004, pp. 45-55.

3. S. Ozen, M. Fimoff, C. Pladdy, M. D. Zoltowski, and S.M. Nerayanuru, "Approximate Best Linear Unbiased Channel Estimation for Multi-Antenna Frequency Selective Channels with Applications to Digital TV Systems," "Advances in Reduced-Rank Adaptive Beamforming," *SPIE 2004 Defense and Security Symposium*, Orlando, Florida, **SPIE Proc. Digital Wireless Communications VI**, 12-16 April 2004, pp. 33-44.

4. H. Jung and M. D. Zoltowski, "Semi-Blind Channel Estimation for Zero-Padded OFDM Systems with Asynchronous Interferers," *SPIE 2004 Defense and Security Symposium*, Orlando, Florida, **SPIE Proc. Digital Wireless Communications VI**, 12-16 April 2004, pp. 251-260.

5. Peilu Ding; Zoltowski, M.D.; Fimoff, M.; "Preconditioned conjugate gradient based fast computation of indirect decision feedback equalizer," *IEEE International Conference on Acoustics, Speech, and Signal Processing, Proceedings (ICASSP 2004)*, Montreal, Canada, Volume: 4 , 17-21 May 2004, Pages: 1001 - 1004.

6. Hyejung Jung; Zoltowski, M.D.; "On the equalization of asynchronous multiuser OFDM signals in fading channels," *IEEE International Conference on Acoustics, Speech, and Signal Processing, Proceedings. (ICASSP 2004)*, Montreal, Canada, Volume: 4 , 17-21 May 2004, Pages: 765 - 768.

7. Santos, E.; Zoltowski, M.D.; "On low rank MVDR beamforming using the conjugate gradient algorithm," *IEEE International Conference on Acoustics, Speech, and Signal Processing, Proceedings. (ICASSP 2004)*, Montreal, Canada, Volume: 2 , 17-21 May 2004, Pages: 173 - 176.

8. E. L. Santos and M. D. Zoltowski, "Adaptive Beamforming with Low Sample Support via Indirect Dominant Mode Rejection," *Second IEEE Sensor Array and Multichannel Signal Processing Workshop (SAM 2004)*, Barcelona, Spain, 18-21 July 2004.

9. E. L. Santos and M.D. Zoltowski, "Adaptive Beamforming with Parametric estimation of the Correlation Matrix," *The Eleventh IEEE Digital Signal Processing Workshop* Taos Ski Valley, New Mexico , August 1-4, 2004.

10. E. L. Santos and M. D. Zoltowski, "Advances in Indirect Dominant Mode Rejection Adaptive Beamforming" *IEEE Military Communications (MILCOM 2004)*, Monterey, CA, Oct.31-Nov.3 2004.

11. E. L. Santos, Y. Liang and M. D. Zoltowski, "Power Spectrum Estimation via Modified Indirect Dominant Mode Rejection," *Proc. of 42nd Annual Allerton Conference on Communications, Systems, and Computing*, Monticello, IL, Sep.29-Oct.1 2004.

12. E. L. Santos, Y. Liang and M. D. Zoltowski, "Power Spectrum Estimation via Modified Indirect Dominant Mode Rejection," *Proc. of 42nd Annual Allerton Conference on Communications, Systems, and Computing*, Monticello, IL, Sep.29-Oct.1 2004.

13. P. Ding and M. D. Zoltowski, "Pilot-Less Carrier Offset Recovery for 8-VSB Robust to Multipath Propagation"," *Proc. of 42nd Annual Allerton Conference on Communications, Systems, and Computing*, Monticello, IL, Sep.29-Oct.1 2004.

14. H. Jung and M. D. Zoltowski, "Semi-blind Multi-channel Identification in Asynchronous Multi-user OFDM Systems," accepted to *Thirty-Eighth Annual Asilomar Conference on Signals, Systems, and Computers*, Monterey, CA, 7-10 Nov. 2004.

15. C. Pladdy and M. D. Zoltowski, "Taylor Series Approximation for Low Complexity Semi-Blind BLUE Channel Estimates for the General Linear Model with Applications to DTV," *Thirty-Eighth Annual Asilomar Conference on Signals, Systems, and Computers*, Monterey, CA, 7-10 Nov. 2004.

16. H. Jung and M. D. Zoltowski, "Semi-blind Multi-channel Identification in Asynchronous Multi-user OFDM Systems," *Thirty-Eighth Annual Asilomar Conference on Signals, Systems, and Computers*, Monterey, CA, 7-10 Nov. 2004.

17. H. Jung and M. D. Zoltowski, "Timing and Frequency Offset Estimation in Asynchronous Multi-user OFDM Systems," *2004 IEEE Military Comm. Confer. (MILCOM)*, Monterey, CA, Oct. 31-Nov. 3 2004.

18. Yifan Liang and M. D. Zoltowski, "Adaptive Spatial Spectrum Estimation via Conjugate Gradients and Dominant Mode Rejection Beamforming" *IEEE Global Telecommunications Conference (GlobeCom 2004)*, Dallas Texas, Volume: 4, 29 Nov.-3 Dec., 2004, Pages:2630 - 2634.

22 INTERACTIONS/TRANSITIONS:

22.1 A. Participation/presentations at meetings, conferences, seminars, etc

- see conference papers listed in Section 5.2

- **Chairman: Sensor Array and Multichannel Technical Committee of IEEE Signal Processing Society.** http://www.engr.uconn.edu/ willett/barney.html#SECTION1 Elected for two year term, 1 January 2005 - 31 December 2006. TC Chairs automatically become members of the *Technical Directions Committee* of the IEEE SPS. Previously served as Vice-Chair, 1 Jan. 2003 - 31 Dec. 2004, with primary functions: coordinating SAM TC nominations for SPS awards and new member elections.

- **Guest Editor**, Special Issue of *IEEE Signal Processing Magazine* on "Knowledge Based Systems for Adaptive Radar Detection, Tracking and Classification." Co-Guest-Editors are Fulvio Gini and J. Scott Goldstein. During November and December of 2004 we reviewed white papers and selected a subset for full paper submission. The special issue is scheduled to be printed in 2006. (This is also listed under External Service; it is listed here since Kent viewed this as an honorary position.)

- **Co-Chair**, *Signal Processing for Communications Symposium* of **IEEE Globecom 2004**, Co-Chairs: Joseph Cavallaro and J.M.H. Elmirghani. Globecom ran in Dallas, TX, 29 Nov. - 3 Dec. 2004. (This item is listed under External Service; it is listed here since Kent viewed this as an honorary position.)

- **Technical Program Co-Chairman for SAM 2006: IEEE 2006 Sensor Array and Multichannel Workshop.** SAM-2006 runs 12-14 July 2006 in Waltham, MA; conference website: www.sam2006.org

- **Keynote Address: IEE 2004 International Conference on Waveform Diversity and Design.** http://www.ieee.org/organizations/society/sp/techachv.html , Selected to deliver keynote address at IEE 2004 Waveform Diversity Conference in Edinburgh, Scotland, 8-10 November 2004.

- Served on the **Awards Board** of the IEEE Signal Processing Society.

- Served on the **Advisory Council for the Department of Electical and Computer Engineering at Drexel University.**

22.2   C. Transitions

Dr. Bruce Suter and CITE at Rome Labs continue to assess the performance of the Conjugate-Gradient based reduced rank filtering schemes developed as part of this project.

23   NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

None.

24   HONORS/AWARDS

1. **Keynote Address: IEE 2004 International Conference on Waveform Diversity and Design.** http://www.ieee.org/organizations/society/sp/techachv.html , Selected to deliver keynote address at IEE 2004 Waveform Diversity Conference in Edinburgh, Scotland, 8-10 November 2004.